Geotechnical and Structures Laboratory

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Improved Concrete Cutting and Excavation Capabilities for Crater Repair

Phase 1

Haley P. Bell, Lulu Edwards, Jay F. Rowland, Blake Andrews,
Quint S. Mason, and Craig A. Rutland

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Final report

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Abstract

The US Army Engineer Research and Development Center was tasked by the US Air Force Civil Engineer Center to improve the saw cutting and excavation production rates of crater repairs in thick portland cement concrete (PCC) pavements for airfield damage repair (ADR) scenarios. The concrete cutting and excavation rates, along with the required manpower, using Caterpillar SW45 and Sw60 wheel saws and Caterpillar and Volvo excavators, respectively, in 18-in.-thick PCC pavement did not meet the required production rates during the 2009 Operational Utility Assessment (OUA) in Avon Park, FL. The current ADR techniques, tactics, and procedures (TTPs) indicate cutting of pavement around a crater should be completed in 22 min or less, and excavation (breaking and removal) of the repair area should be completed in 23 min or less for an 8.5- by 8.5-ft crater. Various equipment (e.g., wheel saws, excavators, rock splitter, anchors, etc.) and methods were evaluated for sawing and removing concrete and base course material in 18- and 24-in.-thick PCC and 5-in.-thick hot-mix asphalt. This report presents the technical evaluation of various sawing and excavation equipment and methods for improving the efficiency of removing damaged pavement associated with crater repair.

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Preface

This study was conducted for the US Air Force's Civil Engineer Modernization Program sponsored by Headquarters, Air Combat Command, Langley Air Force Base, VA. Headquarters, US Air Force Civil Engineer Center (AFCEC), located at Tyndall Air Force Base, FL, provided funding for the research project described in this report, and Dr. Craig Rutland from that organization provided guidance during the project.

The work was performed by the Airfields and Pavements Branch (APB) of the Engineering Systems and Materials Division (ESMD) with quality control testing provided by the Materials Testing Center, both of the US Army Engineer Research and Development Center- Geotechnical and Structures Laboratory (ERDC-GSL). Jeb S. Tingle (APB) was the ERDC Airfield Damage Repair program manager. At the time of publication, Dr. Gary L. Anderton was Chief, APB; Dr. Larry N. Lynch was Chief, ESMD; and Dr. David A. Horner was the Technical Director for Force Projection and Maneuver Support. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Dr. David W. Pittman.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
mils	0.0254	millimeters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

1 Introduction

1.1 Background

In March 2002, the Joint Airfield Damage Repair Working Group identified the lack of certification of existing airfield damage repair (ADR) methods for C-17 aircraft as the number one issue requiring immediate attention. The US Air Force (USAF) Air Mobility Command funded the US Army Engineer Research and Development Center (ERDC) to evaluate existing ADR expedient repair technologies under C-17 aircraft loads.

The general objective of the USAF ADR Modernization Program was to update the Air Force's ADR capability through development of new ADR solutions that are scalable to the threat or damage.

The ADR program has been assessing technologies, materials, and methods needed to support repairs of up to 120 small craters (8.5 by 8.5 ft) on runway and taxiway surfaces within 3 hr (objective) or 6.5 hr (threshold) after an attack. The ADR process can be divided into seven general steps: 1) crater assessment, 2) initial debris removal, 3) marking of upheaval, 4) saw cutting, 5) excavation, 6) backfill, and 7) capping. After the initial crater assessment, each process is executed by separate teams, and which should ideally take a similar amount of time for optimal efficiency and to achieve a continuous work flow. If one process requires a longer length of time, then the teams performing the subsequent tasks will be required to wait, thus slowing the entire ADR process.

Results combined from previous demonstrations and evaluations were used to create the techniques, tactics, and procedures (TTPs) manual describing the processes and requirements of crater repair. The TTPs indicate cutting of pavement around a small crater using two saws should be completed in 22 min or less, and excavation (breaking and removal) of the repair area should be completed in 23 min or less. Based on the previous demonstrations, the breaking time averaged 16 min or less, and the removal time averaged 11 min or less.

Minimal testing and evaluation of crater repair methods has been conducted in thick pavement surfaces. It was determined that the portland cement concrete (PCC) cutting and excavation rates in thick PCC (18 in.)

did not meet the required production rates for optimal efficiency and continuous work flow during the 2009 Operational Utility Assessment (OUA) in Avon Park, FL (Priddy et al. 2013b). During this demonstration, cutting in thick PCC was determined to be more difficult when dowels were present.

In general, the OUA demonstration validated that the new materials, equipment, and procedures are capable of meeting the required ADR threshold timeline of repairs (6.5 hr) and sustaining both fighter and cargo aircraft traffic. Based on the results of the OUA, the decision to begin refinement to achieve the objective timeline of 3 hr and procurement of the new ADR equipment was made by the USAF.

1.2 Objective and scope

The objective of this project was to develop improved equipment and/or TTPs to saw and excavate small craters with average dimensions of 8.5 by 8.5 ft in 18- and 24-in.-thick PCC and 5-in.-thick hot-mix asphalt (HMA) concrete while using minimal manpower. A full-scale test section was constructed of 18-in.-thick PCC, 24-in.-thick PCC, and 5-in.-thick HMA surfaces over crushed limestone base course material. Dowel bars were installed along the transverse joints of the PCC. Various combinations of equipment were tested and evaluated to determine the most efficient use of equipment and manpower for sawing and excavating bomb-damaged pavements.

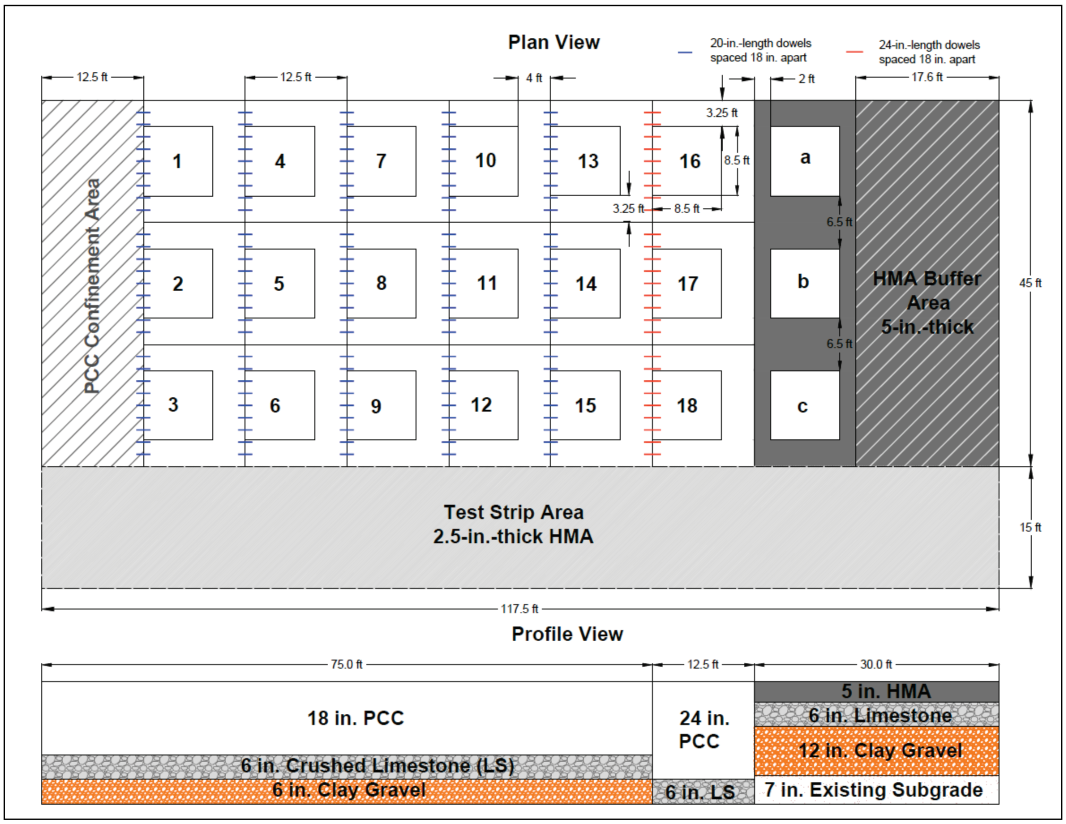
This report provides information for the following:

1. Specification of required capabilities
2. Description of test site
3. Description of evaluated equipment
4. Testing matrix and evaluation results

2 Test Section Description and Characterization

A full-scale test section was constructed of 18- and 24 in.-thick PCC and 5-in.-thick HMA to provide a testing area for purposes of evaluating sawing and excavation equipment and the development of updated TTPs of crater repair. The test section was located on ERDC's Poorhouse property. The plan and profile views of the test section are shown in Figure 1. Planned locations for the simulated repairs are also shown in this figure.

Figure 1. Plan and profile views of test section.



2.1 Test site preparation

The site for the test section was cleared of existing vegetation and a previous test section constructed on the site was removed (Figure 2). The existing subgrade was leveled prior to construction with a 0.8 percent grade in the profile (east to west) and 0.3 percent grade south to north to allow for drainage. A drainage ditch was also constructed off the side of the center of the section (depicted in the far right, center of Figure 2). For both the HMA and PCC sections, 6 in. of crushed limestone was used as the base layer, and clay gravel was used for the subbase of the 18-in.-PCC and the HMA section. The existing subgrade served as the subbase of the 24-in.-thick PCC section. Each layer was compacted to a target of 95 percent modified Proctor density or to the point that in-place density did not increase with additional compactive effort. A Caterpillar CS433E vibratory smooth drum roller and a Wacker WP 1550 W plate compactor were used for compaction (Figure 3).

Figure 2. Excavation for test site construction preparation.

Figure 3. Compaction of base using a vibratory smooth drum roller and plate compactor.

2.2 Laboratory characterization

The materials for each foundation layer were characterized in the laboratory. The grain size distribution curves are included in the appendix in Figure A1 to Figure A3. The Unified Soil Classification System defined in ASTM D2487-11 (2011) was used to classify the subgrade as a brown clay (CL), the clay gravel subbase of the 18-in.-PCC and the HMA sections as a reddish-brown clayey sand (SC) with gravel, and the limestone base as a gray gravel (GP-GM) with silt and sand. The subgrade material was varied throughout the section, so the material of the majority of the section was used for the characterization.

The liquid limit, plastic limit, and plasticity index were determined using ASTM D4318-10 (2010). The limestone and clay gravel were non-plastic, but the subgrade material had a liquid limit of 38, plastic limit of 23, and plasticity index of 15.

The modified Proctor compaction test was completed according to ASTM D1557-12 (2012) for each layer of the test section and is summarized in Table 1.

Table 1. Modified proctor compaction test result summary.

Material	Maximum dry density (pcf)	Optimum moisture (%)
subgrade (CL)	117.3	13.5
clay gravel subbase (SC)	130.6	7.6
limestone base (GP-GM)	145.0	5.3

2.3 Field characterization

The existing subgrade and base materials were characterized using different in situ methods at the test locations indicated in Figure 4, labeled as test point (TP) a, b, c, d, and e.

In situ California bearing ratio (CBR) tests were performed at the locations listed in Table 2 in accordance with ASTM D 4429-04. All CBR proving rings were calibrated prior to and after the completion of field testing, and all rings remained in calibration throughout testing. The field CBR tests were conducted using a truck modified to support the field-deployed CBR testing equipment and loaded with lead weights of a sufficient magnitude to produce the required reaction force. A series of three CBR test replicates were performed at each location.

Figure 4. Test points for subgrade and base measurements.

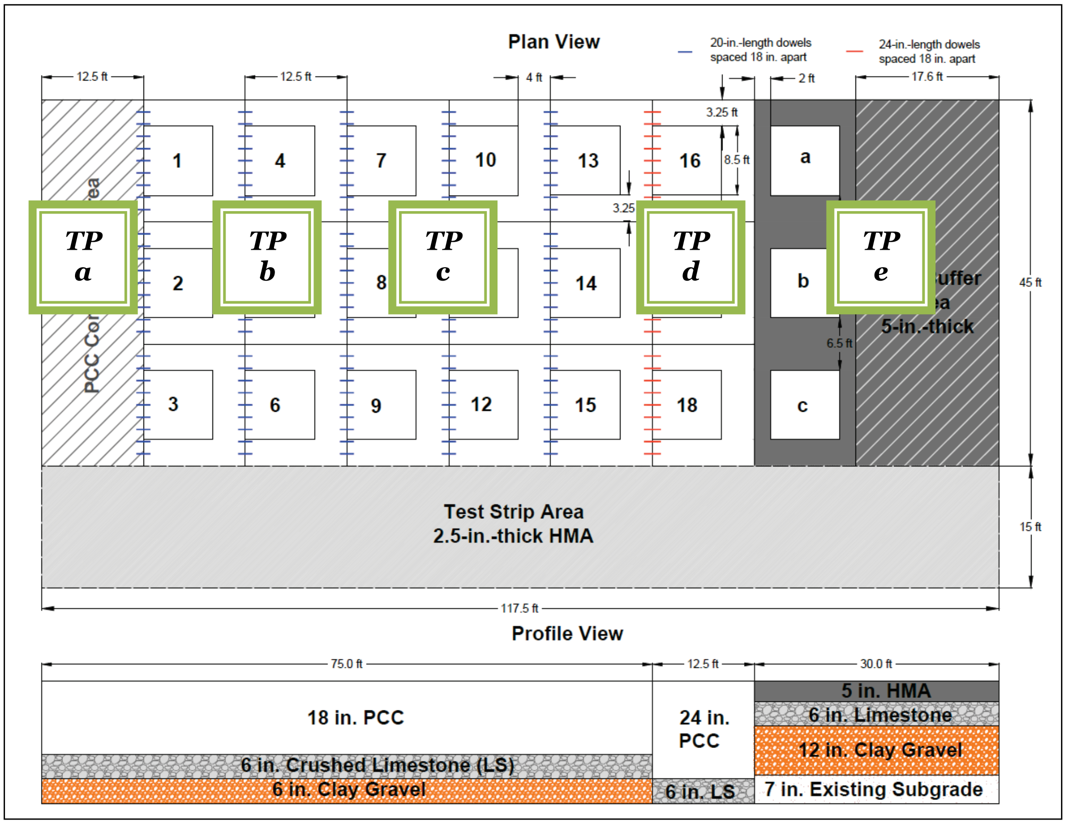


Table 2. In situ CBR tests.

Pavement Layer	Test Point*	Test Replicate Number	CBR (%)	Average CBR (%)
Subgrade	TP b	1	2.0	2.0
		2	2.0	
		3	2.0	
Clay gravel subbase	TP b	1	15.0	14.7
		2	14.0	
		3	15.0	
Clay gravel subbase	TP c	1	15.0	13.8
		2	13.8	
		3	12.5	

*Test point locations can be found in Figure 4

Dynamic cone penetrometer (DCP) tests were conducted to measure the in situ soil strength. The tests were completed in accordance with ASTM D6951 (2003). The DCP had a 60-deg cone with a base diameter of 0.79 in.

The test procedure involved placing the DCP cone point on the surface and recording a baseline measurement to the nearest 5 mm. The 17.6-lb hammer was then raised and dropped 22.6 in. onto the anvil, which drove the penetrometer rod and cone into the soil. Depth of cone penetration measurements and number of hammer blows were recorded approximately every inch (25 mm) or whenever any noticeable change in penetration rate occurred. A DCP strength index in terms of penetration per hammer blow was calculated for each measurement interval. The DCP index was then converted to a CBR percentage using the correlation described in Equation 1. The CBR value ranges from 0 to 100 percent and provides an index of relative soil strength with depth. A CBR value of 100 is equivalent to the bearing capacity of a properly compacted, dense-graded, crushed aggregate.

$$CBR(\%) = \frac{292}{DCP^{1.12}} \tag{1}$$

DCP measurements were taken for each layer of the pavement sections the day before PCC placement and are tabulated in Table 3. The subgrade and subbase CBRs measured using the DCP were higher than those measured using traditional CBR tests because the DCP tests were conducted on compacted material.

Table 3. CBR values of the pavement layers as measured using DCP.

Test Point Location	Subgrade CBR (%) Replicates 1, 2, 3	Subgrade Average CBR (%)	Subbase CBR (%) Replicates 1, 2, 3	Subbase Average CBR (%)	Base CBR (%) Replicates 1, 2, 3	Base Average CBR (%)
TP a	30.0, 30.0, 30.0	30.0	40.0, 25.0, 10.0	25.0	100.0, 100.0, 100.0	100.0
TP b	30.0, 8.0, 15.0	18.0	30.0, 10.0, 15.0	18.0	100.0, 100.0, 100.0	100.0
TP c	8.0, 8.0, 10.0	9.0	20.0, 20.0, 20.0	20.0	100.0, 100.0, 100.0	100.0
TP d	7.0, 6.0, 20.0	11.0	N/A	N/A	100.0, 70.0, 100.0	90.0
TP e	14.0, 11.0, 13.0	13.0	13.0, 11.0, 13.0	12.0	13.0, 13.0, 12.0	13.0

Nuclear density and moisture measurements were collected with a Troxler® 3430 nuclear gauge. The gauge contained two radioactive sources: Cesium-137 for density measurement and Americium-241: Beryllium for determining moisture content. Density and moisture content of the subgrade (Table 4), subbase (Table 5), and base (Table 6) were measured as specified in ASTM D6938-10 (2010). Each layer was measured after compaction, with the exception of the base (Table 6), which was measured the day prior to PCC placement.

Table 4. Nuclear density gauge test results on the subgrade.

Test Point Location	Depth* (in.)	Wet Density* (pcf)	Dry Density* (pcf)	Moisture* (pcf)	Moisture* (%)
TP a	6.0	135.2	131.7	3.4	2.6
TP b	6.0	119.7	98.4	21.4	21.7
TP d	6.0	130.2	122.3	7.9	6.4
TP e	6.0	122.3	117.7	4.6	3.9

*average of three test replicates

Table 5. Nuclear density gauge test results on the clay gravel subbase.

Test Point Location	Depth* (in.)	Wet Density* (pcf)	Dry Density* (pcf)	Moisture* (pcf)	Moisture* (%)
TP a	6.0	135.6	122.8	12.8	10.4
TP b	6.0	131.3	119.1	12.1	10.2
TP c	6.0	131.6	119.5	12.2	10.2

* average of two test replicates

Table 6. Nuclear density gauge test results on the crushed limestone base course.

Test Point Location	Depth* (in.)	Wet Density* (pcf)	Dry Density* (pcf)	Moisture* (pcf)	Moisture* (%)
TP a	6.0	145.5	136.8	8.6	6.3
TP b	6.0	151.6	143.6	8.0	5.6
TP c	6.0	149.6	142.2	7.4	5.3
TP d	6.0	147.4	141.6	5.8	4.1
TP e	6.0	144.4	137.3	7.1	5.2

*average of three test replicates

2.4 PCC construction

The PCC pavement, 18 and 24 in. thick, was constructed in January 2012, of an airfield-quality concrete complete with dowel rods installed along the transverse joints. Eighteen slabs were 18 in. thick, and three slabs were 24 in. thick; each slab was 12.5 by 15 ft. Dowel baskets with epoxy-coated dowel rods made of grade 60 steel were used. For the 18-in.-thick PCC, 20-in.-long, 1.25-in.-diam rods were spaced 18 in. apart at a depth of 9 in. For the 24-in.-thick PCC, 24-in.-long, 2-in.-diam rods were spaced 18 in. apart at a depth of 12 in. The slab dimensions, dowel dimensions, and dowel spacings were in accordance with DOD specifications, UFC 3-260-02, for PCC airfield pavements (HQ Army, Navy, Air Force 2001). ASTM A615 (2009) and ASTM A775 (2007) were used for dowel specifications.

PCC construction work was completed by Dark Horse Construction, LLC from DeSoto, MO. The PCC mixture was produced using a local Federal Aviation Administration (FAA) mix design used at the Jackson-Evers International Airport, MS. The mix was a 650 psi flexural strength (4,000+ unconfined compressive strength (UCS)) mixture using limestone (Figure A4). During placement, test specimens were prepared in accordance with ASTM C39 (2010) for compressive cylinders and ASTM C78 (2010) for flexural beams. Laboratory data for this mixture are included in Table 7. The PCC was placed using a pump truck (Figure 5), consolidated with 2-in. spud vibrators, and screeded with a self-powered, vibratory truss screed. A maximum slump of 7 ± 1 in. was specified, and concrete trucks delivering batches that did not meet the specification were rejected. Fresh property data were taken periodically, with the average slump measuring 7.8 in. and the average air content measuring 5.8 percent. The PCC section was completed with a light broom finish, coated with a curing compound, and then saw-cut to provide transverse and longitudinal joints. The joints were saw-cut approximately 17 hr after the concrete placement. The 18-in.-thick section was saw-cut to a depth of 5 in., and the 24-in.-thick section was saw-cut to a depth of 6.5 in. A white-pigmented curing compound meeting the ASTM C309-11 (2011) specifications was used.

Table 7. Laboratory PCC data.

Modulus (ksi)	28-Day	6,018.0
	90-Day	6,250.0
UCS (psi)	28-Day	7,622.0
	90-Day	8,319.0
Flex Strength (psi)	28-Day	1,039.0
	90-Day	1,021.0
Specific Gravity		2.324
Density (pcf)		144.7

Figure 5. PCC placement.

2.5 HMA construction

The HMA section was constructed in April 2012 adjacent to the PCC area of the test section. The pavement structure thickness consisted of 5 in. of HMA, 6 in. of crushed limestone base material, and 12 in. of clay gravel subbase all over the existing subgrade. The HMA consisted of 5.3 percent of PG 67-22 asphalt cement blended with -3/4 in. crushed gravel (25 percent), stone sand (25 percent), coarse sand (15 percent), #7 limestone (15 percent), and #11 limestone (20 percent).

The asphalt construction work was completed by APAC of Vicksburg, MS. The HMA construction took place in two areas of the test section, where the first area was 15 ft by 117.5 ft by 2.5 in. thick, and the second area was 30 ft by 45 ft by 5 in. thick. The first area (15 ft by 117.5 ft by 2.5 in. thick) was used as the test strip and was paved first and placed in one lift. The second area of HMA was used as the test section and was placed in two 2.5-in.-thick lifts.

Compaction between lifts was completed with a Caterpillar CB-534D double drum roller (Figure 6), Ingersoll Rand PT-125R pneumatic roller, and Ingersoll Rand DD-28HF vibratory double drum compactor (Figure 7). Density was measured with the Troxler nuclear moisture-density gauge and was determined to be adequate for the purposes of this test. The laboratory mix properties were out of specification limits resulting in a tender mix and some movement of the material during compaction (Table 8 and Table 9). The base course was uneven and had some poorly compacted or wet areas resulting in some movement of material during compaction and some unevenness of the final surface. Two nuclear gauge readings were taken with a Troxler 3440 in each location and averaged (Table 10), and cores (Table 11) were taken in areas where the base was firmly compacted. The data indicated that sufficient compaction was achieved. In-place density should be 92-95 percent of the theoretical maximum density (TMD). Final thickness of the compacted mat was on the order of 5 in. with one area being slightly thinner on the order of 4.5 in. thick. The condition of the HMA test section did not affect the research.

Figure 6. HMA compaction with a double drum vibratory compactor.

Figure 7. HMA compaction with a pneumatic roller and vibratory compactor.

Table 8. Sieve analysis.

Sieve Size (mm)	% Passing JMF[a]	% Passing QC[b]
25.00	100.0	100.0
19.00	100.0	100.0
12.50	96.0 ± 8.0	96.9
9.50	85.0 ± 8.0	90.4
4.75	68.0 ± 8.0	75.3
2.36	54.0 ± 6.0	58.6
1.18	38 ± 6	-----
0.60	28 ± 6	29.1
0.30	15 ± 6	16.4
0.15	7 ± 2	-----
0.075	4.9 ± 2	6.3

[a]job mix formula

[b]quality control, performed by APAC

Table 9. Laboratory data.

Data	JMF[a]	QA[b]
Binder content *(P_b)*	5.3 ± 0.5	5.45
Maximum theoretical specific gravity *(G_{mm})*	2.461	2.445
Effective specific gravity *(G_{se})*	2.668	2.655
Asphalt binder absorption *(P_{ba})*	0.87	0.68
Effective asphalt content *(P_{be})*	4.47	4.81
Material passing No. 200 sieve *(P_{200}/P_{be})*	1.04	1.24
Bulk specific gravity *(G_{mb})*	2.363	2.404
Air voids *(V_a)*	4 ± 1.0	1.7
Voids mineral aggregate *(VMA)*	14.3	12.9
Voids filled with asphalt *(VFA)*	72.0	87.0

[a]job mix formula

[b]quality assurance, performed by ERDC

Table 10. Nuclear density gauge test results on final HMA lift.

Test Area	Dry Density (pcf)	Wet Density (pcf)	Moisture (pcf)	Moisture (%)
1	139.8	147.5	7.8	5.6
2	135.8	143.7	8.0	5.9
3	127.4	136.0	8.7	6.8
Avg.	134.3	142.4	8.1	6.1

Table 11. Density measurement of cores.

Core No.	G_{mb}	% TMD
1	2.340	95.7
2	2.347	96.0
3	2.357	96.4
Avg.	2.348	96.0

3 Evaluated Technologies

A variety of equipment was assessed for potential in improving the speed of the cutting and excavation processes of crater repair in PCC and HMA. The following sections describe the technologies that were included in the evaluation. The concrete chain saw, rock splitter, and concrete expansion anchors were new technologies that were being evaluated for this test. All other technologies were used in previous ADR testing and demonstrations.

3.1 Caterpillar 279C compact track loader

Caterpillar 279C compact track loaders (CTL), or skid steers, are high-flow, rubber-tracked machines with quick disconnect fittings that are used extensively in the current ADR TTPs (Figure 8). The quick disconnect allows attachments to be switched out rapidly without the use of tools. The multi-purpose machines are employed for many of the ADR processes including rapidly cutting around the upheaval of bomb-damaged pavement using wheel saw attachments, breaking pavement using the hammer attachment (Figure 9), removing debris using bucket attachments, screeding pelletized asphalt caps with the asphalt screed attachment, or cleanup with the broom attachments. Specifications for the machine and hammer can be found in Table 12 and Table 13, respectively.

Figure 8. Caterpillar CTL279C, operating a SW45 wheel saw attachment.

Figure 9. Caterpillar CTL279C with the H65D S hammer attachment.

Table 12. Caterpillar 279C CTL specifications.

Net power	82 hp
Operating weight	9,495 lb
Rated operating capacity	3,200 lb at 50% tipping load
Travel speed	5.0 mph
Tipping load	6,483 lb
Breakout force, tilt cylinder	7,308 lb
Maximum loader hydraulic pressure*	4,061 psi
Maximum loader hydraulic flow*	33 gal/min

*For high flow XPS models

Table 13. Caterpillar H65D S hammer specifications.

Impact energy class	950 ft-lbf
Operating weight	818 lb
Tool diameter	2.56 in.
Acceptable oil flow	11-28 gpm
Operating pressure	2,465 psi
Impact rate	700 - 2,000 blows per min
Carrier weight limits	6,610 - 19,800 lb

3.2 Caterpillar SW45 and SW60 wheel saws

The CTLs are equipped to operate the Caterpillar SW45 (Figure 8) and/or SW60 wheel saw attachments. These wheel saw attachments produce a

3.5-in.-wide cut. The SW45 has an 18-in.-maximum depth cut, and the SW60 has a 24-in.-maximum depth cut. The wheel saws are equipped with a hydraulic side-shift (26 in.) to assist in wheel positioning.

The SW60 is a custom wheel saw that has been modified for ERDC. Commercial off-the-shelf SW60 models have a 6-in.-wide blade, but this cut is too wide for the purposes of the ADR program. The SW60 was modified to provide a 3.5-in.-wide cut. Specifications for both machines are shown in Table 14.

Table 14. Wheel saw specifications.

Parameter Specifications	Caterpillar SW45	Modified Caterpillar SW60
Overall width	71 in.	74 in.
Overall height	57 in.	69 in.
Length	78 in.	88 in.
Weight	2,295 lb	2,750 lb
Wheel width (without teeth)	3 in.	3 in.
Required hydraulic flow range	24-42 gpm	26-42 gpm
Optimal hydraulic pressure range	2,611-4,351 psi	2,611-4,351 psi
Wheel torque at maximum pressure	4,944 lb•ft	5,931 lb•ft
Wheel speed at maximum flow	115 rpm	96 rpm
Number of teeth	64 per wheel	70 per wheel
Maximum depth of cut	18 in.	24 in.
Side shift travel	26 in.	26 in.

During recent equipment testing conducted at ERDC, the Caterpillar 149-5763 teeth were determined to be the most efficient teeth to use for saw-cutting PCC. These teeth are classified as cold planer teeth and are not the concrete teeth normally sold for the wheel saws. The conical bits, or teeth, used on the SW45 and SW60 for cutting (part number 149-5763) are made with a carbide tip, specifically designed for milling concrete, solid limestone, and ultra-hard rock (Figure 10). There are 64 teeth needed for the SW45, and 70 teeth needed for the modified SW60.

Replacing teeth is necessary when the carbide bits become worn. A punch tool is used with a mallet to remove the teeth, and the teeth are tapped in place with the mallet, as shown in Figure 11.

Figure 10. Wheel saw teeth, CAT part number 149-5763.

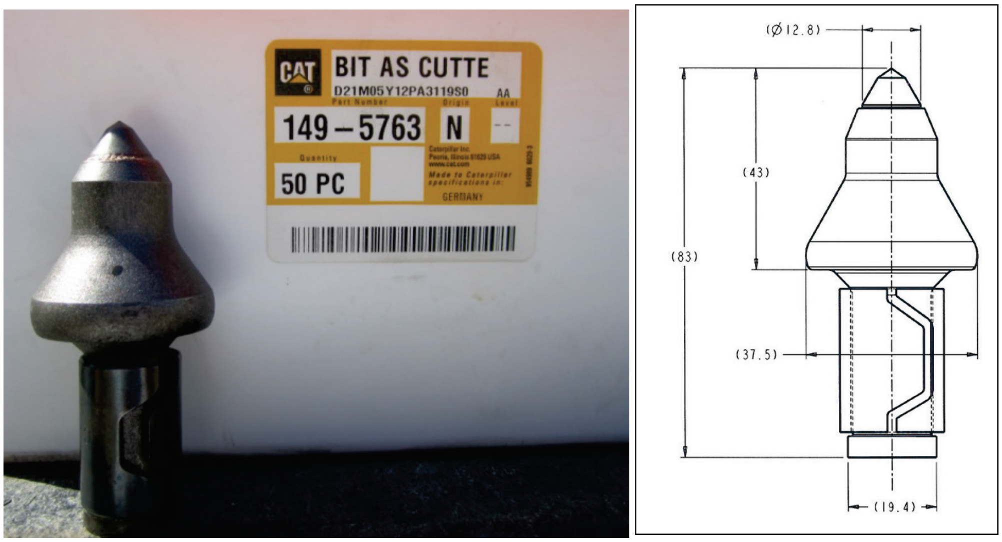
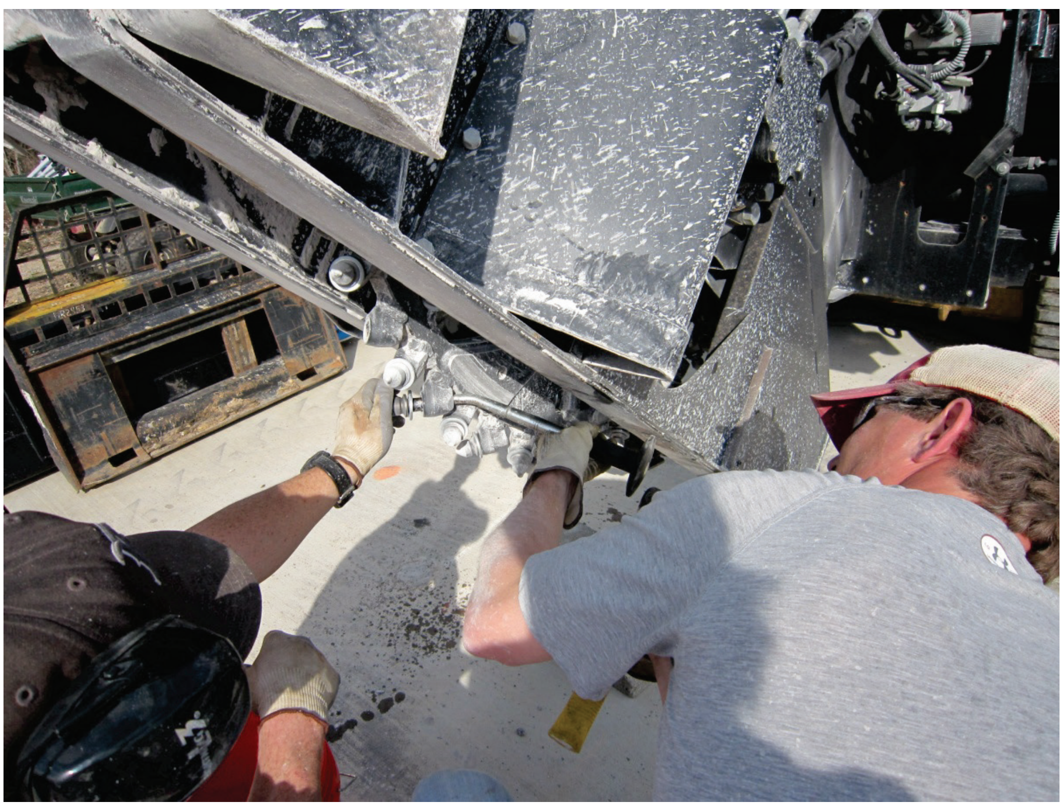


Figure 11. Replacing teeth on a SW45 saw.



3.3 Husqvarna FS 6600D walk-behind saw

The Husqvarna FS 6600D (Figure 12) is employed in the ADR TTPs when dowels are encountered in the removal of damaged pavement. The self-propelled walk-behind wheel saw is equipped with a 42-in.-diam diamond blade. The Husqvarna saw is propelled by a John Deere motor with 66 hp and weighs 1,892 lb. The maximum cutting depth is 17.5 in. using a 42-in.-diam diamond-tipped blade. An external water supply is required to cool the blade while the saw is in operation.

Figure 12. Husqvarna FS 6600D.

3.4 Volvo EW180D Excavator

A Volvo EW180D wheeled excavator (Figure 13) is used in the ADR TTPs to break the PCC and excavate the broken PCC and underlying material. Wheeled excavators are preferred to tracked excavators for crater repair purposes because they minimize damage to the existing pavement around the repairs. The excavator is equipped with quick-disconnect fittings for the hammer and bucket work tool attachments. Table 15 presents the specifications of the Volvo EW180D wheeled excavator.

The concrete was broken using a Volvo HB1400 hammer (Figure 13) with a chisel point and a moil point. Two different sized toothed buckets, 24- and 36-in.-wide, were used for removing disturbed material (Figure 14). The teeth on the 24- and 36-in.-wide buckets were 9.5 and 7.75 in. long, respectively. The excavator was equipped with quick-disconnect fittings for the hammer and bucket work tool attachments. Specifications for the Volvo HB1400 hammer are listed in Table 16.

Figure 13. Volvo EW180D excavator with Volvo HB1400 hammer.

Figure 14. Excavator 24-in.-wide bucket (left) and 36-in.-wide bucket (right).

Table 15. Volvo EW180D excavator specifications.

Net power	171 hp
Maximum torque	559 ft•lb at 1,500 rpm
Breakout force	30,574 lbf
Maximum digging reach	32.0 ft
Maximum digging depth	20.8 ft
Maximum travel speed	22 mph
Operating weight	36,200 to 40,600 lb

Table 16. Volvo HB1400 excavator hammer specifications.

Impact energy	2,500 lb•ft
Operating weight	2,932 lb
Tool diameter	4.92 in.
Acceptable oil flows	32 to 45 gpm
Oil pressure	1,958 to 2,103 psi
Impact rate	450 to 800 blows per min
Excavator weight limits	39,683 to 57,320 lb

3.5 Caterpillar 416D and 430D backhoes

A Caterpillar 416D backhoe with a moil point Caterpillar H90 hammer (Figure 15, Table 17) was evaluated in the current study for its ability to break up the concrete during the excavation process. The Caterpillar 430D backhoe was equipped with a 24-in.-wide rotating bucket capable of turning 180 deg (Figure 16). The teeth were 6.5 in. long on the rotating bucket. The efficiency of the rotating bucket was compared to a stationary bucket and repositioning of the backhoe.

The 430D backhoe was selected to be evaluated, because it is more likely to be readily available on military bases. No hammer was available for the 430D backhoe, so the Caterpillar 416D was used as a comparable model.

3.6 Front-end loader

A front-end loader was employed for removing sawed pavement using anchoring systems and general cleanup. The Caterpillar 966G was used. The specifications can be found in Table 18.

3.7 Concrete chain saw

A 695F4 ICS utility chain saw, designed for concrete cutting, was evaluated as a supplemental tool to aid in the saw-cutting process (Figure 17). The concrete chain saw is equipped with a 16-in.-long bar with diamond chains and weighs approximately 21 lb. Gasoline and water are required to operate the saw. The utility chain saw is operated in the same manner as a standard chain saw.

Figure 15. Caterpillar 416D backhoe with moil point hammer.

Figure 16. Caterpillar 430D backhoe with rotating bucket.

Table 17. Caterpillar H90 hammer specifications.

Energy class	1,200 ft-lb
Operating weight	1,298 lb
Tool diameter	3.3 in.
Acceptable oil flow	16-39 gpm
Operating pressure	1,958 psi
Impact rate	500 -1,450 blows per min
Carrier weight limits	15,400 – 26,400 lb

Table 18. Front-end loader (Caterpillar 966G) specifications.

Bucket capacity	5.25 yd3
Operating weight	50,410 lb
Static tipping load (full turn)	30,870 lb

Figure 17. Concrete chain saw.

3.8 Rock splitter

A Darda rock splitter (size 9) was evaluated in this study as an alternative and/or supplement to breaking the PCC using an excavator hammer. The rock splitter is capable of breaking the PCC into smaller pieces for easier removal. The technology requires a 49-hp compressor, drill, drill bits, fuel, paste, and a generator. To effectively crack the concrete, a 1.75-in.-diam drill bit is required to drill a hole 18 in. deep. The rock splitter's wedge set is inserted into the predrilled hole. Paste is used on the wedge set of the rock splitter for ease of inserting and removing in the drilled holes. Using hydraulic pressure, the wedge is driven forward to force the counter wedges apart, splitting the pavement slab (Figure 18). Occasionally, the rock splitter is able to split the pavement slab in another direction, normally at 90 deg from the original break when the device is rotated.

Figure 18. Darda rock splitter.

3.9 Concrete expansion anchors

An anchor pullout system using concrete expansion anchors was evaluated in this study for its ability to excavate the thick concrete. The anchor pullout system process involved drilling two 1.25-in.-diam holes (12-in.-maximum depth) into the PCC (Figure 19), cleaning the hole with compressed air, installing the concrete expansion anchors (Simpson's Torq-Cut™ TCAP751458) in the drilled holes (Figure 20), cutting off excess threaded rod using a band saw, attaching the lifting hoists to the anchors with a torque wrench (Figure 21 and Figure 22), attaching the shackles to the endless round slings (Figure 23), and attaching the slings or a chain to a piece of powerful equipment such as a front-end loader (Figure 24), excavator, or forklift (CAT TL1055). Using the anchor pullout system requires that the pavement be saw-cut full-depth before removal. This anchor pullout system is used for removal of slabs prior to placement of precast panels for airfield pavement repairs (Bly et al. 2013).

Figure 19. Drilling hole for anchors.

Figure 20. Driving concrete expansion anchor into drilled PCC.

Figure 21. Tightening anchors with torque wrench.

Figure 22. Finishing up with the lifting hoists and shackles.

Figure 23. Attaching straps to the shackles.

Figure 24. Straps attached to front-end loader, ready to remove the broken slab.

4 Field Evaluation

The saw and excavation crater repair technologies were evaluated in February and March 2012 for the PCC and June 2012 for the HMA. Craters were simulated using the excavator with the chisel point hammer. The simulated craters ranged in diameter from 2 to 4.5 ft. No upheaval was generated during testing. In a war time scenario, upheaval is expected. Figure 25 shows a simulated crater. An approximate 8.5- by 8.5-ft square was marked outside of the centered simulated craters as a guide for the saws to follow.

Figure 25. Simulated crater.

Table 19 through Table 21 present the matrix used for evaluating the crater sawing and excavation equipment in 18-in.-thick PCC, 24-in.-thick PCC, and 5-in.-thick HMA, respectively. All methods are discussed further in the following section. The crater repair preparation process was divided into three categories: saw cutting, breaking, and removing. In some cases, a supplemental method (e.g., rock splitter or use of relief cuts) was utilized. All events were timed. Each method or technology was tested at least twice to obtain an average production rate. The operators varied for most equipment with the exception of the excavator and wheel saws; one operator for each of these machines was used throughout testing. Table A1 in Appendix A presents a more detailed test matrix for the evaluation including the operators, test dates, and essential notes.

Table 19. 18-in.-thick PCC test matrix.

Crater No.	Saw Cutting	Supplemental Tool	Breaking	Removing
1	SW45; walk-behind saw at joint	n/a	excavator with chisel hammer	excavator with 24-in. bucket
2	SW60; walk-behind saw at joint	n/a	CTL with moil hammer	430D backhoe with 24-in. bucket
3	SW45; walk-behind saw at joint	n/a	416D backhoe with moil hammer initially; finished using excavator with chisel hammer	excavator with 24-in. bucket
4	SW60; walk-behind saw at joint	n/a	anchors – front-end loader (3 pieces; 2 at 1 time)	430D backhoe with rotating bucket
5	SW60; walk-behind saw at joint	n/a	excavator with chisel hammer	excavator with 36-in. bucket
6	SW45; walk-behind saw at joint	n/a	anchors on half slabs - front-end loader and excavator	excavator with 36-in. bucket
7	SW60; walk-behind saw at joint	walk-behind saw relief cuts ("t" pattern)	416D backhoe with moil hammer	excavator with 36-in. bucket
8	SW60; walk-behind saw at joint	n/a	excavator with moil hammer	excavator with 24-in. bucket
9	walk-behind saw on two adjacent sides; SW45 on two sides	SW45 relief cuts ("x" pattern)	none	excavator with 36-in. bucket
10	SW60; walk-behind saw at joint	SW45 relief cut across middle	anchors - fork lift	excavator with 36-in. bucket
11	SW45; walk-behind saw at joint	n/a	excavator with chisel hammer	excavator with 36-in. bucket
12	SW45; walk-behind saw at joint	n/a	416D backhoe with chisel hammer then CTL with moil hammer then excavator with moil hammer	excavator with 36-in. bucket
13	walk-behind saw on two adjacent sides; SW45 on two sides	SW45 relief cut (bucket width); extra relief cut across center perpendicular to bucket width cuts	416D backhoe with chisel hammer initially; rock splitter (once) on half slab	430D backhoe with 24-in. bucket
14	SW45; walk-behind saw at joint	n/a	rock splitter (3 holes)	430D backhoe with 24-in. bucket
15	walk-behind saw on two opposite sides; SW45 on two sides	n/a	excavator with chisel hammer	430D backhoe with rotating bucket

Table 20. 24-in.-thick PCC test matrix.

Crater No.	Saw Cutting	Supplemental Tool	Breaking	Removing
16	SW60; walk-behind saw at joint	n/a	excavator with chisel hammer	excavator with 36-in. bucket
17	SW60; walk-behind saw at joint	rock splitter (5 holes)	excavator with chisel hammer	430D backhoe with rotating bucket
18	SW60; walk-behind saw at joint	n/a	excavator with moil hammer	excavator with 36-in. bucket

Table 21. 5-in.-thick HMA test matrix.

Crater No.	Saw Cutting	Supplemental Tool	Breaking	Removing
a	SW45	n/a	279C CTL with moil hammer	416D backhoe with bucket
b	SW45	n/a	416D backhoe with hammer	416D backhoe with bucket
c	SW45	n/a	416D backhoe with hammer	416D backhoe with bucket

The TTPs were based on the previous demonstrations (Priddy et. al. 2013a and Priddy et. al. 2013b). In the TTPs, the goal for the saw cutting rate was 1 ft/min or faster. The goal for the breaking was 16 min or less, and the removal process goal was 11 min or less.

While testing, the timing data were compared to the previous demonstrations (LOUA1, LOUA2, and OUA). A significant difference in sawing rates and breaking times was noted. Most of these differences can be attributed to the concrete mix. The particular limestone mix used for this field testing had a high UCS (8,319 psi at 90 days) and high flexural strength (1,021 psi) and appeared to slow the processes down. This mix was much stronger than anticipated as the mix design specified a UCS of 5,000 psi and flexural strength of 650 psi.

4.1 Saw cutting

Three saws, the SW45 wheel saw, the SW60 wheel saw, and the Husqvarna walk-behind saw, were evaluated for their efficiency and maneuverability of cutting around small craters. The walk-behind saw was the only machine used to cut along the doweled joints and was normally used simultaneously with the wheel saws (Figure 26). The wheel saws attached to a CTL were mainly used to cut along the non-doweled repair edges. For the ADR modernization program, wheel saws are preferred over walk-behind saws, because they are easier to transport, require no water, and they make excavation easier because of the resulting wide cut width.

OUA results (Priddy et. al. 2013b), however, indicated that a walk-behind saw was required to cut through dowels, and as a result, walk-behind saws were included in the ADR TTPs.

Figure 26. Walk-behind saw with wheel saw, operating simultaneously.

Relief cuts within the already sawed crater repair area were evaluated to determine if they increased the production rates of the excavation process. Relief cuts were explored in previous ADR demonstrations (LOUA2) for thick PCC (Priddy et. al. 2013a). Four craters received relief cuts, three using the SW45 wheel saw and one using the walk-behind saw, all in varying patterns. Three patterns were tested: a “t pattern” (Figure 27), “x pattern” (Figure 28), and combination of a center relief cut with a bucket-sized relief cut in the center (Figure 29).

Other than the walk-behind saw on the doweled joints, the SW60 wheel saw attachment on the CTL was the only saw used on the 24-in.-thick PCC due to the wheel saw’s maximum cut depth of 24 in. The SW45 wheel saw attachment on the CTL was the only saw used on the HMA; in most scenarios, the HMA will not be thick enough to require the use of the SW60 wheel saw. The teeth on the wheel saws and blade on the walk-behind saw were replaced approximately every three craters.

The concrete chain saw was not used in the test section, but it was evaluated as a supplemental technology by cutting through large broken pieces of PCC. The chain saw was tested for its production rate and its ability to saw through PCC and dowel rods. Figure 30 shows the chain saw cutting through the PCC.

Figure 27. Relief cuts on Crater 7 in a “t pattern,” dividing the crater into quadrants.

Figure 28. Relief cuts on Crater 9 in an “x pattern,” dividing the crater into quadrants.

Figure 29. Combination of bucket size relief cuts and a center relief cut on Crater 13.

Figure 30. Utility chain saw cutting through PCC.

4.2 Breaking

4.2.1 Hammers

The excavator, CTL, and backhoe were all evaluated for their ability to break up the thick saw-cut PCC and HMA. Moil and chisel point hammers were tested to determine if any differences in efficiency may be gained using one hammer type over the other. The excavator with the chisel hammer was evaluated on six PCC slabs, and the excavator with moil hammer was evaluated on three PCC slabs. The CTL with moil hammer was evaluated on three PCC slabs and one HMA slab. The backhoe with moil and chisel hammers were both evaluated on two PCC slabs. The breaking up of the saw-cut HMA was tested using the backhoe with the moil hammer on two slabs (Figure 31).

4.2.2 Concrete expansion anchors

The concrete expansion anchors were used on three craters, with the front-end loader (Figure 32), CAT TL1055 extendable boom forklift (Figure 33), and excavator (Figure 34) to remove the slabs. A front-end loader was used for three half-slabs. One of the half-slabs was broken into two pieces, and the front-end loader was able to remove these two smaller pieces in one pull-out. The excavator and extendable boom forklift lifted out half-slabs using the concrete expansion anchors. Only half a slab or less was attempted with this method because of the limits of the equipment used to remove the slabs.

Figure 31. Breaking HMA pavement with backhoe.

Figure 32. Anchor pull-out using front-end loader.

Figure 33. Removing with the forklift (CAT TL1055).

Figure 34. Removing with the excavator.

4.2.3 Rock splitter

A rock splitter was also evaluated for its ability to break the thick PCC. The rock splitter was tested on two 18-in.-thick PCC slabs and one 24-in.-thick PCC slab. The rock splitter was used once in the 18-in. PCC in Crater 13 to break a half-slab into two pieces (Figure 35). This broke the slab into manageable pieces for the 430D backhoe to remove with ease. For the 18-in. PCC in Crater 14 (Figure 36), the rock splitter was used in three locations and turned 90 deg in each location to produce two breaks, which broke the slab into a total of six manageable pieces for the 430D backhoe to remove. For the 24-in. PCC slab, the rock splitter was used in five locations in Crater 17 (Figure 37). In each location, the rock splitter was turned 90 deg to produce two breaks, and the entire slab was broken into eight smaller pieces.

Figure 35. Remaining half slab broken in two pieces with rock splitter (Crater 13).

Figure 36. Rock splitter in three locations, resulting in six broken pieces (Crater 14).

Figure 37. Slab after five rock splitter instances (Crater 17).

4.3 Removing

The removal of the broken PCC and HMA slabs and their underlying material was assessed using an excavator and backhoes. The excavator was evaluated with a 24-in.-wide bucket and a 36-in.-wide bucket (Figure 14). Each bucket was equipped with teeth of different lengths. The 24-in.-wide bucket had 9.5-in.-long teeth, and the 36-in.-wide bucket had 7.75-in.-long teeth. The excavator with the 36-in.-wide bucket was tested on eight PCC slabs, and the excavator with the 24-in.-wide bucket was tested on three PCC slabs.

Two backhoes with similar capabilities were evaluated; one backhoe was equipped with a standard 24-in.-wide bucket, while the other backhoe was equipped with a rotating 24-in.-wide bucket with 6.5 in. long teeth. Both backhoes were each assessed on three PCC slabs. Only the backhoe with the standard 24-in.-wide bucket was tested on the HMA (Figure 38).

Figure 38. Removal of HMA with backhoe.

5 Results and Discussion

Each technology was evaluated at least twice within the test section. The saw blades and saw teeth were replaced often (approximately every three craters) to avoid testing with dull blades and teeth. The production rates in ft/min or minutes for each evaluated technology are presented as the minimum time, the maximum time, and the average time.

5.1 18-in.-thick PCC

5.1.1 Sawing

The results of the sawing and excavation evaluation in the 18-in.-thick PCC are presented in Table 22. All saws evaluated in the 18-in.-thick PCC (Husqvarna FS 6600D walk-behind saw and Caterpillar SW45 and SW60 wheel saws) met the saw-cutting goal of 1 ft/min.

The walk-behind saw was assessed along the saw-cut doweled joints of every slab (18 times) and in the PCC without dowels five times. The walk-behind saw was able to cut through the PCC with the 1.25-in.-diam steel dowel rods effectively and efficiently, with an average rate of 1.46 ft/min. The minimum rate of 0.91 ft/min along a doweled joint was due to problems with the water supply, which happened more than once in the evaluation and is likely to occur in threat scenarios. A new blade was on the walk-behind saw when the maximum rate of 2.54 ft/min along a doweled joint was recorded.

The walk-behind saw cut through the PCC with dowels (1.46 ft/min) almost as fast as it cut through the PCC without dowels (1.59 ft/min). However, two passes of the walk-behind saw were necessary for some cuts to saw full depth. The 2.29 ft/min maximum rate, achieved using the walk-behind saw in only the PCC, was with one pass of the saw along the line. This was for a relief cut, so it was not as important to keep the saw in a straight line. It was often difficult for the operators to keep the walk-behind saw cutting in a straight line, even in the existing saw-cut joints.

Table 22. 18-in.-thick PCC timing results.

	SAWING (ft/min)				BREAKING (min)					REMOVING (min)		
	WBS: Doweled Joint	WBS: Non-doweled Joint	SW45[a]	SW60[a]	Excavator with Chisel Hammer	Excavator with Moil Hammer	CTL with Moil Hammer	Anchor Drilling[b]	Rock Splitter Drilling[b]	Excavator with 24-in. Bucket	Excavator with 36-in. Bucket	Backhoe with 24-in. Bucket
Min	0.91	1.04	0.75	0.84	5.17	4.00	53.50	2.67	10.17	17.33	9.00	14.00
Max	2.54	2.29	1.43	1.37	7.67	6.72	53.50	4.15	14.50	22.07	15.83	25.50
Average	1.46	1.59	1.06	1.02	6.42	5.36	53.50	3.23	12.48	19.02	11.41	18.50

[a]Only those slabs cut using Caterpillar's (part number 149-5763) cold planer teeth were used for these metrics

[b]Time to drill one hole

At the beginning of the tests, the standard concrete teeth were used on the Caterpillar wheel saws. However, the teeth tested on the wheel saws in the past and shown to be the best for crater repair purposes are Caterpillar's cold planer teeth (part number 149-5763). Caterpillar's concrete teeth (part number 227-7340) are typically sold with the wheel saws. The teeth are shown side by side for comparison in Figure 39. The concrete teeth were used on the first five craters tested, and the remaining craters were cut with the cold planer teeth. However, the wheel saw results presented in Table 22 are based solely on the testing with the cold planer teeth.

Figure 39. Concrete saw teeth (left) and cold planer teeth (right).

On average, the concrete teeth's cutting rate using the SW45 wheel saw was approximately 8 percent slower compared to the cold planer teeth in the 18-in.-thick PCC (0.98 versus 1.06 ft/min). On average, the concrete teeth's cutting rate using the SW60 wheel saw was approximately 20 percent slower compared to the cold planer teeth in the 18-in.-thick PCC (0.85 versus 1.02 ft/min).

The concrete teeth were also not as durable as the cold planer teeth. The production rates of the concrete teeth in the 18-in.-thick PCC decreased, on average, 66 percent from cutting one crater (three 9-ft-long lines) to cutting a second crater (an additional three 9-ft-long lines). The production rates of the cold planer teeth in the 18-in.-thick PCC decreased, on average, 29 percent from cutting one crater to cutting a second crater. The concrete teeth were not tested in the 24-in.-thick PCC.

The following information describes results using only the cold planer teeth on the wheels saws. The SW60 was tested with 12 cuts and was slightly slower in the 18-in.-thick PCC than the SW45, which was tested with 19 cuts. The average production rates of the SW45 and SW60 wheel saws in the 18-in.-thick PCC were 1.06 and 1.02 ft/min, respectively. It took approximately 4 min for both wheel saws to plunge full depth through the 18-in.-thick PCC before they began forward movement. Teeth were replaced, on average, every three craters (more often than necessary), and new cold planer teeth were on the SW45 wheel saw when its maximum rate of 1.43 ft/min was recorded. The maximum rate of 1.37 ft/min using the SW60 was also achieved after new teeth were put on the wheel saw.

The maximum cut depth for the SW45 wheel saw was 18 in., and the maximum cut depth for the SW60 wheel saw was 24 in. However, in some cases, it was difficult to achieve full-depth cuts. This was likely due to substantial concrete debris buildup around the saw or the operator not keeping the saw completely horizontal and flush with the surface.

The utility chain saw was not used on the test section, but it was evaluated on a large piece of PCC with an installed 1.25-in.-diam steel dowel rod. The concrete chain saw successfully sawed through the concrete and dowel. The production rate of the hand-held saw through only the PCC was approximately 0.065 ft/min. It took approximately 4.5 min to cut through the 1.25-in.-diam steel dowel rod. This is far from the goal of 1 ft/min; however, the saw did cut through the concrete and dowel rod successfully (Figure 40). The chains had to be tightened often during use but were still in good shape after sawing through the PCC and dowel rod as shown in Figure 41.

5.1.2 Breaking

Six technologies were evaluated for their efficiency in breaking up the 18-in.-thick PCC. The results are presented in Table 22. The excavator with the moil point hammer attachment was the fastest method with an average break time of approximately 5.5 min. The excavator with the chisel point hammer attachment followed with an average break time of 6.5 min. However, both hammers seemed to work well. The moil point hammer was tested two times compared to the chisel point hammer, which was tested five times. The average number of breaks for the moil and chisel point hammers in the 18-in.-PCC was 11 and 13, respectively.

Each crater was broken into bucket-sized pieces, as shown in Figure 42, for efficient removal. Smaller pieces required more effort and increased the removal time. Larger pieces resulted in a faster removal time but were risky because the larger pieces were likely to be dropped and would damage the surrounding parent slab.

Figure 40. Utility chain saw cut through PCC and dowel rod.

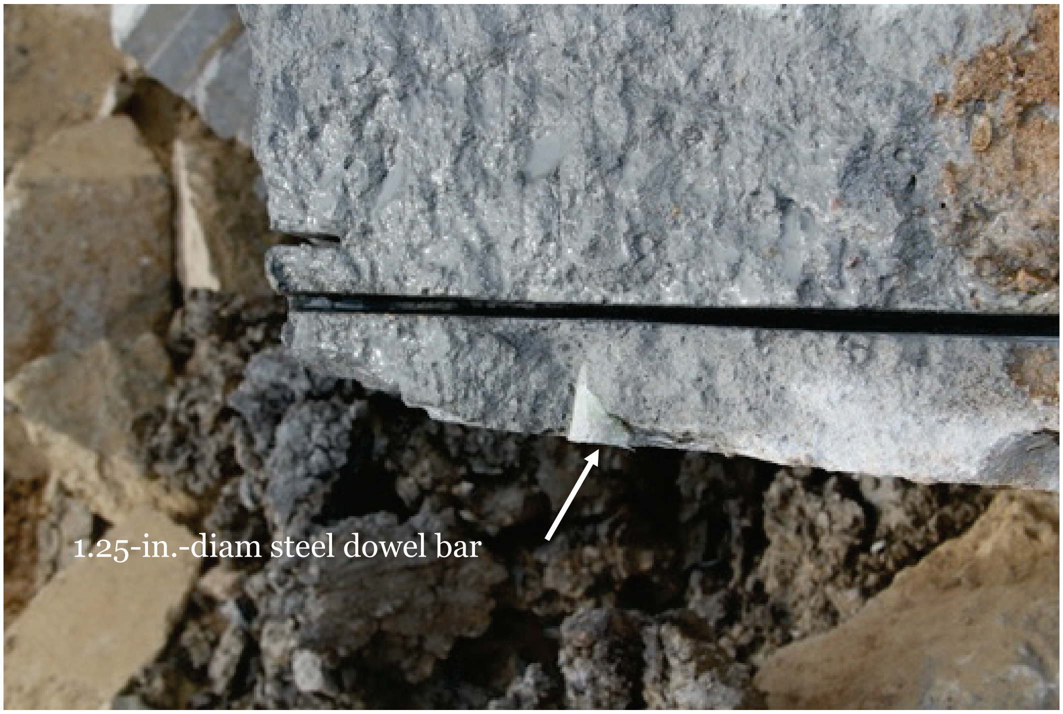


Figure 41. Utility saw blades after cutting through PCC and dowel rod.

Figure 42. Example of broken slab with excavator with chisel hammer (Crater 5).

The CTL with the moil point hammer was evaluated in two repairs. The CTL hammer broke the PCC of the first repair in approximately 53.5 min. Although slow, the CTL hammer was able to penetrate through the PCC. The CTL hammer was not able to successfully break up the PCC in its second repair. The evaluation was stopped after 50 min, because the hammer jammed and very little breakage had occurred.

The PCC must be saw-cut full depth from corner to corner (at least on three sides) for the anchor pull-out method to be employed. The existing saw-cut doweled joints were cut to only approximately 17 in. of the 18-in.-thick PCC. Two of the three repairs tested with the anchor system were saw-cut using the SW60 wheel saw to ensure the PCC was cut full depth. Every 8.5- by 8.5-ft repair required at least four drilled holes with one relief cut down the middle, with each created using a wheel saw. Table 22 presents the average time it took to drill one hole, about 3.5 min. Approximately 14 min was spent drilling holes for one PCC crater removal. The remainder of the installation process of anchor placement, attaching shackles, tightening screws, and attaching straps, was also slow and cumbersome. The machinery tested, front-end loader (Figure 32), forklift (Figure 33), and excavator (Figure 34), were each able to lift half of a slab (two drilled anchors). Figure 43 shows the repair area after all PCC was removed using anchors. Figure 44 shows an installed and deployed anchor in a broken piece of PCC.

Figure 43. Repair area after slab was pulled out by the anchor system technique.

Figure 44. Deployed anchor in broken PCC.

The rock splitter drilling time shown in Table 22 reflects the time it took to drill one 18-in.-deep hole for the rod to be inserted in using a 1¾-in.-diam drill bit. Often, it was necessary to drill more than one hole to break up the saw-cut slab into pieces small enough to be removed. The average time it took to drill one hole was almost 13 min. The drilling was laborious and time consuming; however, the actual splitting of the concrete took less than 30 sec.

Rotating the rock splitter 90 deg after its initial split to try and crack the PCC in the opposite direction was successful about 50percent of the time. During one instance, the rock splitter became jammed after turning it 90 deg, and the excavator hammer had to be brought in to break the PCC away so the rock splitter could be removed from the hole. The rock splitter had to be used in three different drilled holes of one 8.5-by 8.5-ft repair to successfully break up the 18-in.-thick PCC, totaling approximately 39 min just for drilling in one repair.

The backhoe was tested for its ability to break up the 18-in.-thick PCC of four repairs; two with the moil point hammer and two with the chisel point hammer. The backhoe was not successful in breaking up the PCC. The impact force of the hammer was insufficient to penetrate the PCC; it simply chipped away at the surface (approximately 2 in. deep). The only semi-successful attempt was of a repair which already had two relief cuts made by the walk-behind saw. The moil point hammer penetrated into the existing cuts and rocked back and forth enough to break up the PCC into a total of six large pieces, when the slab was already broken into four pieces by the relief cuts. However, this process took almost 48 min indicating that the backhoe is not the ideal piece of equipment for breaking up 18-in.-thick PCC.

5.1.3 Removing

Three techniques for removing the broken PCC and base course material to a depth of approximately 34 in. were evaluated in the 18-in.-thick PCC. The results are presented in Table 22. An excavator equipped with a 36-in.-wide bucket with 7.75-in.-long teeth was the most efficient method of removing the broken PCC and underlying material (approximately 11.5 min). The average removal time was only 30 sec more than the breaking goal of 11 min. The 24-in.-wide buckets on both the backhoe and excavator were not as efficient. The teeth on the 24-in.-wide buckets were 9.5 in. long, and the longer teeth seemed to make it more difficult to lift and remove the initial pieces of broken PCC and the soil material, particularly along the back edge of the excavated repair. The 24-in.-wide bucket is designed for digging ditches, and is shaped accordingly. However, it is not efficient for removing large PCC pieces or the underlying subbase.

On average, the backhoe with the 24-in.-wide bucket, tested four times, took the same amount of time to excavate a repair to 34 in. (19 min) as the excavator with the 24-in.-wide bucket. It appears that the size of the bucket and length of the teeth impact the efficiency of removal more than the power of the equipment.

5.2 24-in.-thick PCC

5.2.1 Sawing

Table 23 shows average production rates of the sawing, breaking, and removal technologies evaluated in the three 24-in.-thick PCC slabs. The walk-behind saw was used along the doweled joints at an average rate of 1.41 ft/min. Although the steel dowels in the 24-in.-thick PCC were 0.75 in. larger in diameter (2 in. diam), the average cut rate was essentially the same as for doweled joints in the 18-in.-thick PCC. The maximum rate of 2.05 ft/min occurred with a new blade. The 0.98 ft/min minimum rate recorded using the walk-behind saw resulted from the operator's inability to keep the saw tracking in the joint.

Table 23. 24-in.-thick PCC timing results.

	SAWING (ft/min)		BREAKING (min)			REMOVING (min)	
	WBS: Doweled Joint	SW60[a]	Excavator with Chisel Hammer	Excavator with Moil Hammer	Rock Splitter Drilling[b]	Excavator with 36-in. Bucket	430D Backhoe with 24-in. Bucket
Min	0.98	0.60	7.02	6.97	9.00	8.63	18.90
Max	2.05	0.99	10.33	6.97	11.38	13.93	18.90
Average	1.41	0.82	8.68	6.97	10.53	11.28	18.90

[a]Only those slabs cut using Caterpillar's cold planer teeth(part number 149-5763) were used for these metrics

[b]Time to drill one hole

The SW60 wheel saw with the cold planer teeth (part number 149-5763) was the only equipment used in the 24-in.-thick PCC. After nine cuts, the average production rate was 0.82 ft/min. This is below the goal of 1 ft/min; however, equipment evaluations had not been conducted in the thicker PCC prior to this study. Due to the location of the 24-in.-thick PCC slabs, three of the nine cuts began with the wheel saw tracks in the compacted limestone surrounding the test section. This may have contributed to the lower average production rate. The cut rates when the wheel saw tracks began on the limestone ranged from 0.60 to 0.83 ft/min compared with 0.70 to 0.99 ft/min when the wheel saw tracks began on the surrounding PCC.

5.2.2 Breaking

The excavator with two different shaped hammers and the rock splitter were evaluated for their ability to break the 24-in.-thick PCC. The results are presented in Table 23. The backhoe was not evaluated in these slabs because it had proven inadequate to break up the 18-in.-thick PCC. The anchoring technique for slab removal was also not tested for fear that the PCC was not cut to the full depth; no available saws were capable of cutting full depth if the PCC happened to be more than 24 in. thick.

Although the excavator with the moil point hammer was evaluated on only one slab, it appears to be the most efficient method for breaking up the 24-in.-thick PCC (7 min). The excavator with the chisel point hammer was evaluated on two slabs and had an average break time of almost 9 min. Both times were under the desired goal of 16 min.

The rock splitter was evaluated on only one of the 24-in-thick slabs. The rock splitter time shown in Table 23 is the average time it took to drill one hole in the PCC. Five holes were drilled in the repair to get the 24-in.-thick PCC broken up enough for removal. The average drilling time for the five holes was almost 11 min. per hole, or almost 55 min total time.

5.2.3 Removing

The excavator with the 36-in.-wide bucket and the backhoe with the 24-in.-wide bucket were evaluated for their ability to remove the 24-in.-thick PCC and underlying soil to a depth of approximately 34 in. The results are presented in Table 23. The excavator was the most efficient piece of equipment to remove the 24-in.-thick PCC and underlying material with an average time of 11.5 min. The maximum time shown in Table 23 was 14 min; this longer time was due to the operator having difficulty removing the first broken piece of PCC. The PCC had been broken up using the excavator with the moil point hammer, and the PCC should have been broken up smaller.

The backhoe was evaluated to determine if the equipment had enough power to lift and remove the 24-in.-thick PCC. Even though the rock splitter was used five times on this slab during the breaking process, the PCC was not broken up enough to remove using the backhoe. The initial removal of the PCC using the backhoe was stopped, and the excavator with the chisel hammer was brought in to break up more of the PCC. The backhoe resumed, and the total removal time was approximately 19 min, which is longer than the current removal goal of 11 min.

5.3 5-in.-thick HMA

5.3.1 Sawing

Three repairs were made in the 5-in.-thick HMA to evaluate the efficiency of crater repair equipment. Table 24 shows the sawing and excavation results. The SW45 wheel saw was the only saw evaluated in the HMA. The average production rate to saw-cut through the HMA was just short of 10 ft/min.

Table 24. 5-in.-thick HMA timing results.

	SAWING (ft/min)	BREAKING (min)		REMOVING (min)
	SW45	CTL with Moil Hammer	416D Backhoe with Chisel Hammer	Backhoe with 24-in. Bucket
Min	7.87	4.00	3.00	15.17
Max	11.90	4.00	4.97	22.75
Average	9.78	4.00	3.99	18.09

5.3.2 Breaking

For breaking, the CTL equipped with the moil point hammer was tested on one repair, while the 416D backhoe with the chisel point hammer was tested on two repairs. The backhoe was selected to be evaluated twice because it is more likely to be readily available on military bases. Both methods had average breaking times of 4 min.

5.3.3 Removing

The backhoe attached with the 24-in.-wide bucket was used for excavating to the 34-in.depth. The average removal time was approximately 18 min, which was nearly the same average removal time as for the 18- and 24-in.-thick PCC repairs (approximately 19 min).

6 Conclusions and Recommendations

ERDC performed full-scale field evaluations of crater repair equipment to identify methods for increasing efficiency of production rates for sawing, breaking, and excavating small craters for repair purposes. It should be noted that the concrete mix had a large effect on the sawing rates and possibly the breaking time as well. The 18- and 24-in.-thick PCC test sections were constructed of limestone aggregate with concrete that had an average 90-day UCS of 8,319 psi and flexural strength of 1,021 psi. These 90-day values were much higher than the mix design specified (UCS of 5,000 psi and flexural strength of 650 psi) and most likely caused the longer sawing rates seen in this study. Pavement constructed of different mixes may produce drastically different rates and efficiency. The following sections present the conclusions and recommendations resulting from the study.

6.1 Conclusions

- The Caterpillar Sw45 and SW60 wheel saws are capable of cutting a maximum of 18 and 24 in. deep, respectively. However, they cut at their maximum depth only when used in the most efficient manner – with minimal concrete debris buildup under the saw with the saw level and with the guard kept at its lowest position continuously. Generally, the SW45 and SW60 wheel saws effectively cut to maximum depths of 17 and 23 in., respectively.
- The performances of the Caterpillar SW45 and SW60 wheel saws on the 18-in.-thick PCC were similar, and their average production rates met the 1 ft/min goal for saw cutting. On average, the SW45 wheel saw cut approximately 4 percent faster than the SW60 wheel saw in the 18-in.-thick PCC.
- The Husqvarna FS 6600D walk-behind saw was capable of cutting through the 1.25- and 2-in.-diam, grade 60 steel, dowel rods in the 18- and 24-in.-thick PCC, respectively. The average production rate exceeded the 1 ft/min goal for saw cutting. PCC constructed with dowel rods had minimal effect on the walk-behind saw's capability to cut thick PCC.
- The average production rate of the Caterpillar SW60 wheel saw on the 24-in.-thick PCC was slightly less than the goal of 1 ft/min. However,

the SW60 wheel saw was the only option tested for saw cutting 24-in.-thick PCC to full depth.

- The Volvo EW180D excavator with the Volvo HB1400 moil point hammer was the most efficient technology for breaking up the 18- and 24-in.-thick PCC and far exceeded the goal of 16 min per repair slab. The Volvo EW180D excavator with the Volvo HB1400 chisel point hammer was also capable of exceeding the production rate goal of breaking up the 18- and 24-in.-thick PCC.
- The Caterpillar 416D and 430D backhoes, using both the moil and chisel point hammers, failed to break up the 18-in.-thick PCC. The impact energy of the largest hammer compatible with the Caterpillar 416D and 430D backhoes was not enough to penetrate the thick PCC; the hammers simply chipped away at the surface.
- Relief cuts using the Caterpillar SW45 and SW60 wheel saws and the Husqvarna FS6600D walk-behind saw were not beneficial to the excavation process. It is more efficient to break up and remove the thick PCC with a hammer mounted on an excavator than it is to replace or supplement the breaking process with relief cuts. If an excavator with a hammer attachment is not available, then the relief cuts could serve as an alternative for breaking the PCC. The relief cut pattern ("x" or "t") does not make a difference, but two relief cuts are required to break the slab into quadrants. However, the subbase would still have to be removed using a backhoe or similar equipment.
- The Volvo EW180D excavator with the 36-in.-wide bucket and 7.75-in.-long teeth was the most efficient technology for removing the thick PCC and underlying debris for small crater repair. The average production rate exceeded the removal goal of 11 min per repair.
- Occasionally, when the Caterpillar SW45 and SW60 wheel saws did not cut full depth, the breaking process would cause the parent slab to crack from the repair corner to the slab corner.
- The rock splitter was capable of cracking the 18-in. PCC full depth; however, the drilling process was slow. The 24-in.-thick PCC was not consistently broken full depth with the rock splitter.
- Although slow, the 695F4 ICS utility chain saw was capable of cutting through PCC and dowel bars. The utility chain saw could be used as a supplement if no other equipment is available for thinner pavements (12 in. or less) but should be used with caution for safety reasons.
- The concrete expansion anchors were successfully used to remove 8.5-ft by 4.25-ft by 18-in. PCC sections using a CAT TL1055 forklift, CAT

966G front-end loader, and the Volvo EW180D excavator; however, the process of installing the anchors was labor intensive and slow.

6.2 Recommendations

- Although the Husqvarna FS6600D walk-behind saw had the fastest production rate when compared to the Caterpillar SW45 and SW60 wheel saws, it is recommended only for use as a backup saw or for cutting through dowel rods. The walk-behind saw requires water and is slower in transporting. Also, using the walk-behind saw makes the removal process slower when compared to a wheel saw due to the width of the cuts. The wider cuts of the wheel saws make it easier for the teeth on the bucket being used for removal to be worked into position for removing the PCC pieces from the saw-cut hole.
- It is recommended that the Volvo EW180D excavator and HB1400 hammer (or their equivalents) be used for breaking up thick PCC. The hammer point should be kept at least 1 ft away from the inside crater repair edges to avoid spalling the surrounding PCC.
- A CTL hammer may be used as backup to the excavator for breaking.
- While the rock splitter is capable of breaking the PCC into more manageable pieces, it is not recommended for the ADR process because of the requirement for additional supporting equipment - the air compressor, generator, drill, and drill bits. Additionally, use of the rock splitter is time-consuming.
- Use the wheeled excavator equipped with a 36-in.-wide bucket and 7.75-in.-long teeth is recommended for removing concrete and material. Use of longer teeth is not advised because they make the removal process more cumbersome.
- While the concrete expansion anchors are versatile in that several different pieces of equipment can be used to lift the concrete slabs out of the crater, their installation is time consuming and requires the use of additional equipment, including a generator, drill, drill bits, anchors, and shackles. Once installed, the anchors cannot be retrieved for reuse, but the shackles are reusable.
- A backhoe with a 24-in.-wide bucket with 6.5-in.-long teeth can be used as backup for removing concrete and material.

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Appendix A: Additional Data

Figure A1. Classification data for subgrade materials.

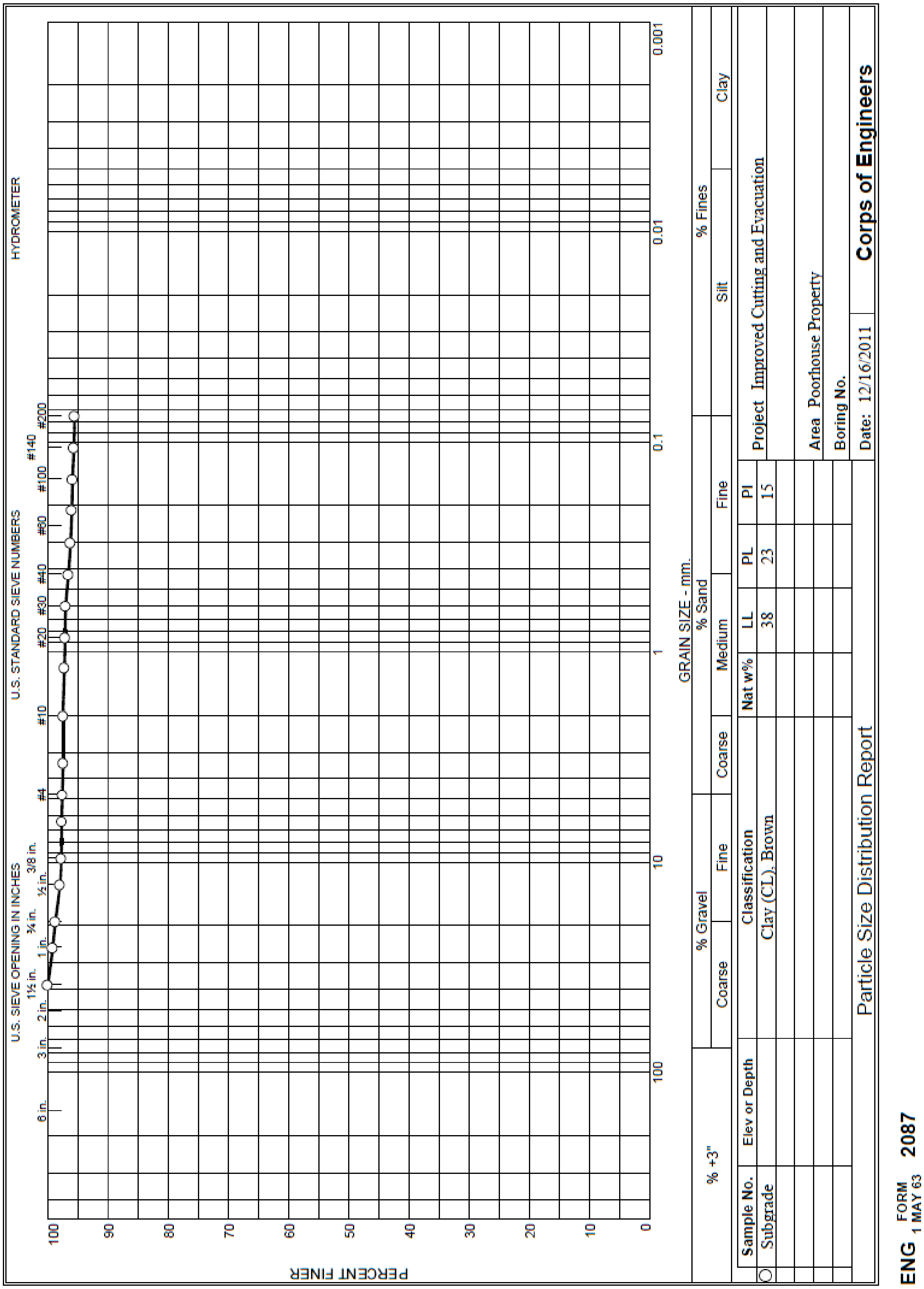

Figure A2. Classification data for clay gravel.

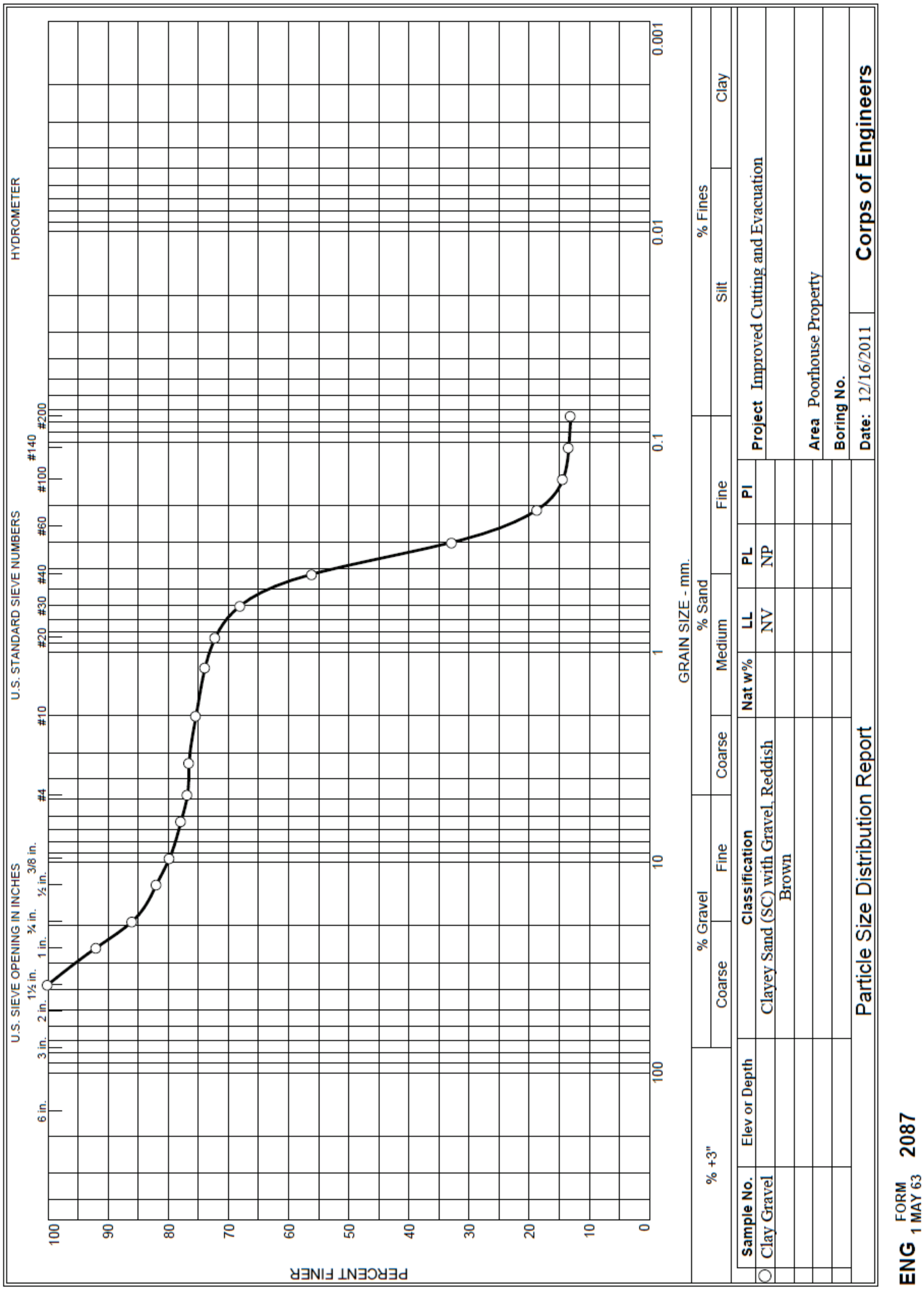

Figure A3. Classification data for limestone.

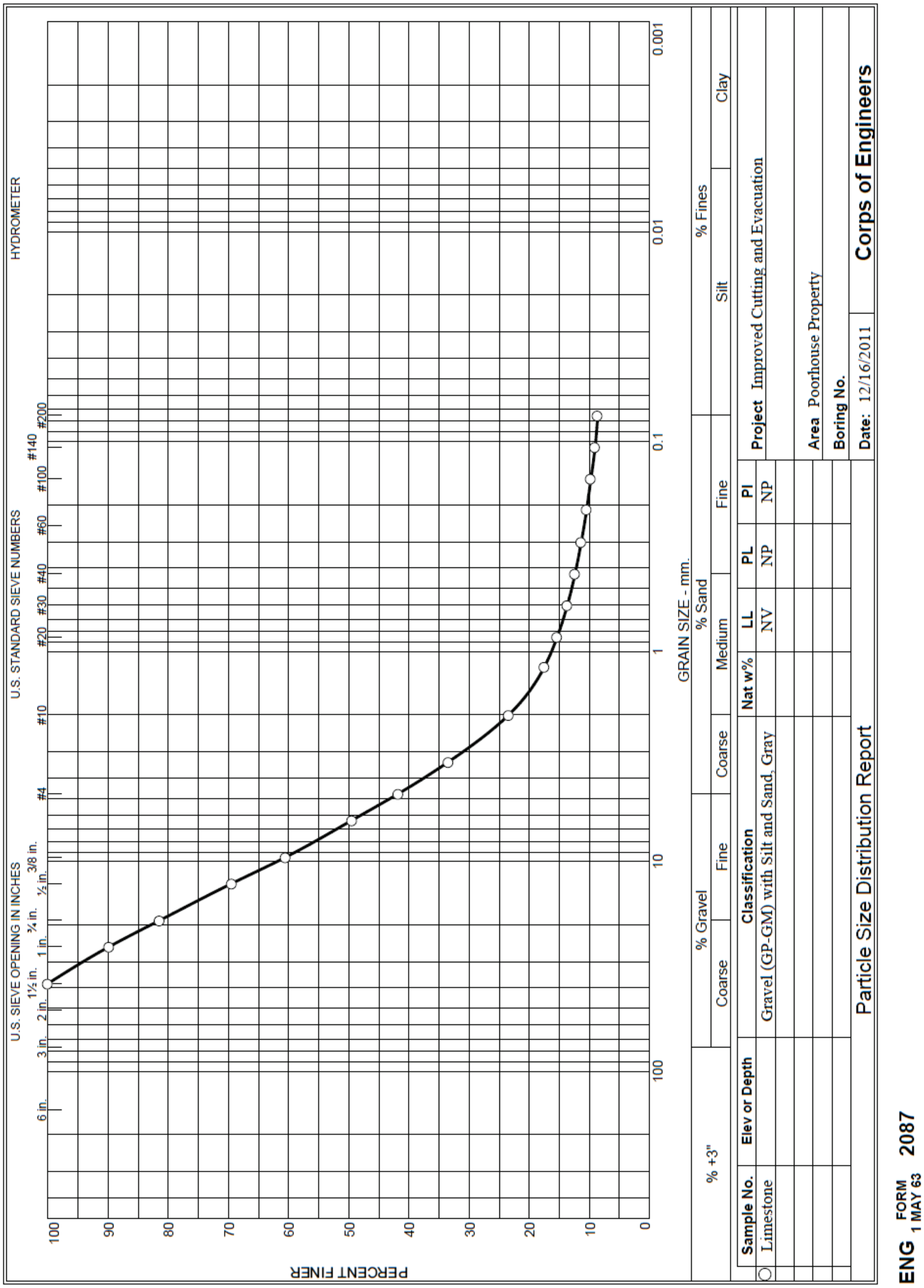

Figure A4. Mix design for PCC section.

MMC Materials, Inc. Since 1927

Construction Type: Paving

Constructor: Darkhorse

Mix Number: V5041961

Specified Slump: 7 inches

Project Description: USACE W912HZ12

Concrete Supplier: MMC Materials

Specified Compressive Strength: 650 flex

Specified Air Content 3 to 6 %

Material Properties and Source

Cementitious Material		Type		Source		Specific Gravity
Portland Cement		II		Holcim		3.15
Fly Ash		C		Headwaters		2.59
GGBFS (Slag)						

Admixtures		Name		Supplier		Dosage, Fl. Oz.
Type A		322 N		BASF		2-5 per cwt.
Type F		7500		BASF		5-9 per cwt
AE		MB90		BASF		3% - 6%
Note: Dosage rate will require adjustments for field and environmental conditions.						

Aggregate Size	Type	Supplier	Sp. Gr. SSD	Sp. Gr. OD	Absorption, %	F.M.
# 57	Stone	Vulcan	2.68	2.67	0.80	
Sand	Natural	Green Bro.	2.60	2.58	0.66	2.65

Batch Quantities

Material	Quantities lb/yd^3 SSD	Absolute Volume ft^3
Cement, lb.	489	2.49
Fly Ash, lb	122	0.75
Mix Water, lb.	245	3.93
Slag, lb.		
Coarse Aggr., lb.	1850	11.06
Fine Aggr., lb.	1225	7.55
Air Content, %	4.5	1.22
Total Mass, lb.	3931	27.00

Water / cementitious material ratio: 0.40

Mix Design Information:

Mix Class 5000 psi. with Air

Comments: 650 Flex

Designed by: Andrew Lester

Title: Regional QA Manager

Organization: MMC Materials

The above mix will meet the specified strength in 28 days when tested, placed, and handled in accordance with current ASTM and ACI standards and recommended practices. Please include this office on the distribution list for concrete test reports.

Figure A5. Mix design for asphalt section.

U.S. Army Corps of Engineers, Engineer Research and Development Center

Mix Type	HMA	Producer:	APAC Vicksburg
Design Specification:		Designer:	ERDC
Date	2/10/2012		
Type Mix	12.5mm		

								AGG BLEND	JOB MIX	SPEC DESIGN RANGE
TYPE	-3/4"	StoneSand	COARSE SAND	#7	#11					
MTL	CR GR	Limestone		Limestone	Limestone					
AGG	APAC	Vulcan	APAC							
SOURCE		Calera								
% USED	25	25	15	15	20			% PASSING	% PASSING	
1.5"/37.5mm	100.0	100.0	100.0	100.0	100.0			100.0	100	
1.0"/25.0mm	100.0	100.0	100.0	100.0	100.0			100.0	100	
3/4"/19.0mm	100.0	100.0	100.0	100.0	100.0			100.0	100	100
1/2"/12.5mm	89.9	100.0	100.0	90.3	100.0			96.0	96	76-96
3/8"/9.5mm	70.5	100.0	100.0	46.1	100.0			84.5	85	68-89
#4/4.75mm	34.4	100.0	97.3	3.7	97.3			68.2	68	53-73
#8/2.36mm	18.2	91.3	90.4	1.6	61.7			53.5	54	38-60
#16/1.18mm	10.8	61.5	85.6	1.5	35.6			38.3	38	26-48
#30/.600mm	6.9	39.2	75.7	1.5	24.1			27.9	28	18-38
#50/.300mm	4.4	21.4	30.8	1.4	17.0			14.7	15	11-27
#100/.150mm	3.0	10.0	4.9	1.3	13.1			6.8	7	6-18
#200/.075mm	2.1	6.4	2.7	1.2	10.8			4.9	4.9	3-6
								%AC	5.30	
Gsa	2.625	2.764	2.653	2.725	2.677			2.688	MIX TEMP	320
Gsb	2.524	2.684	2.600	2.675	2.586			2.609	VOIDS	4.0
%CR +#4	91.2	100	100	100	100			95.5	VMA	14.3
HUMPRATIO								47.4	VFA	72
% CLAY								0.0	Gmm	2.461
PI -#4 MTL									Gsb	2.609
% ABS MOIST	1.56	1.08	0.78	0.69	1.33	0.00	0.00	1.15	Pba (mix)	0.83
	COMP TEMP	(F) 290	300	Mixing Temp	310 330	%Gmm @Nm			Pbe	4.47
ANTI STRIP	NONE	RATE=		% by weight of AC		%Gmm @Ni			D/B	1.0
AC SOURCE	ERG-VICKSBURG	TSR=	85.0	F/E		FAA			Gse	2.668
AC TYPE	PG67-22	Ni:	7	Nd: 75	Nm: 115				Gb	1.030

REMARKS: % FIBER: 0.00%

% Rap Used = 0.0 % AC (RAP) = 0.00 % AC (Add) = 5.30 %AC (Total) = 5.30

Stripping (MT-59)=

The percentage of ERG-VICKSBURG PG67-22 asphalt cement used with the above blend of mineral aggregate for the 12.5mm mix is 5.3 .

Table A1. PCC test matrix with details.

Test No.	Crater No.	Test Date	PCC Thickness (in.)	Crater Dia (in.)	Saw Cutting	Supplemental Tool	Breaking	Removing	Notes
1	1	22-Feb	18	40	SW45 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	excavator with chisel hammer (Les)	excavator with 24-in. bucket (Les)	concrete teeth; new teeth, new blade; 13 breaks
2	3	22-23 Feb	18	54	SW45 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	416D backhoe with moil hammer initially (Les); finished using excavator with chisel hammer (Les)	excavator with 24-in. bucket (Les)	concrete teeth
3	5	23-24-Feb	18	35	SW60 wheel saw (Jay) and walk-behind saw at joint (Blake)	n/a	excavator with chisel hammer (Les)	excavator with 36-in. bucket (Les)	concrete teeth; new teeth, changed blade midway; 13 breaks
4	7	23-24 Feb	18	36	SW60 wheel saw (Jay) and walk-behind saw at joint (Blake)	walk-behind saw relief cuts ("t" pattern) (Mike)	416D backhoe with moil hammer (Les)	excavator with 36-in. bucket (Les)	concrete teeth; crater broken into ~6 large pieces
5	9	24-Feb	18	36	walk-behind saw on two adjacent sides (Les) and SW45 wheel saw on other two sides (Jay)	SW45 wheel saw relief cuts ("x" pattern) (Jay)	none	excavator with 36-in. bucket (Les)	concrete teeth; new teeth, new blade; crater cut into 4 large pieces

Test No.	Crater No.	Test Date	PCC Thickness (in.)	Crater Dia (in.)	Saw Cutting	Supplemental Tool	Breaking	Removing	Notes
6	13	28-Feb	18	47	walk-behind saw on two adjacent sides (Les) and SW45 wheel saw on other two sides (Jay)	SW45 wheel saw relief cut (bucket width) (Jay), and extra relief cut across center perpendicular to bucket width cuts (Les)	416D backhoe with chisel hammer initially (Les); then rock splitter (once) on half slab	430D backhoe with 24-in. bucket (Les)	cold planer teeth; new teeth; slab broken into 2 large pieces and 3 smaller pieces
7	14	28-29-Feb	18	43	SW45 wheel saw (Jay) and walk-behind saw at joint (Blake)	n/a	rock splitter (3 holes)	430D backhoe with 24-in. bucket (Les)	cold planer teeth; new blade; slab broken into 4 large pieces and 2 smaller pieces
8	15	29-Feb	18	43	walk-behind saw on two opposite sides (Blake) and SW45 wheel saw on other two sides (Jay)	n/a	excavator with chisel hammer (Les)	430D backhoe with rotating bucket (Les)	cold planer teeth; new teeth; 15 breaks
9	17	29-Feb - 1 Mar	24	47	SW60 wheel saw (Jay) and walk-behind saw at joint (Les)	rock splitter (5 holes)	excavator with chisel hammer (Jay)	430D backhoe with rotating bucket (Les)	cold planer teeth; new teeth, new blade; rock splitter got jammed - used excavator to break loose
10	2	2-Mar	18	55	SW60 wheel saw (Jay) and walk-behind saw at joint (Blake)	n/a	CTL with moil hammer (Jay)	430D backhoe with 24-in. bucket (Jay)	cold planer teeth

Test No.	Crater No.	Test Date	PCC Thickness (in.)	Crater Dia (in.)	Saw Cutting	Supplemental Tool	Breaking	Removing	Notes
11	4	5-Mar	18	22	SW60 wheel saw (Jay) and walk-behind saw at joint (Mike)	n/a	anchors - front-end loader (3 pieces; two at 1 time)	430D backhoe with rotating bucket (Les)	cold planer teeth; simulated crater after cutting all sides - cracked into 3 pieces
12	6	5-6 Mar	18	27	SW45 wheel saw (Jay) and walk-behind saw at joint (Mike, then Les)	n/a	anchors on half slabs - front-end loader and excavator (Les)	excavator with 36-in. bucket (Les)	cold planer teeth; simulated crater after starting cut with WS - cracked to slab; new drill bit
13	8	9-Mar	18	36	SW60 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	excavator with moil hammer (Les)	excavator with 24-in. bucket (Les)	cold planer teeth; new teeth; 11 breaks
14	18	12-Mar	24	37	SW60 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	excavator with moil hammer (Les)	excavator with 36-in. bucket (Les)	cold planer teeth; 13 breaks

Test No.	Crater No.	Test Date	PCC Thickness (in.)	Crater Dia (in.)	Saw Cutting	Supplemental Tool	Breaking	Removing	Notes
15	12	13-Mar	18	29	SW45 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	backhoe with chisel hammer (Les) then CTL with moil hammer (Jay) then excavator with moil hammer (Les)	excavator with 36-in. bucket (Les)	cold planer teeth; new teeth; 10 breaks with backhoe; 21 breaks with CTL before hammer got jammed; 11 breaks with excavator
16	11	16-Mar	18	28	SW45 wheel saw (Jay) and walk-behind saw at joint (Les)	n/a	excavator with chisel hammer (Les)	excavator with 36-in. bucket (Les)	cold planer teeth; all out crater; new teeth; new blade
17	10	16-Mar	18	46	SW60 wheel saw (Jay) and walk-behind saw at joint (Les)	relief cut across middle using 45-in. wheel saw (Jay)	anchors - fork lift	excavator with 36-in. bucket (Les)	cold planer teeth
18	16	19-Mar	24	44	SW60 wheel saw (Jay) and walk-behind saw at joint (Blake, then Les)	n/a	excavator with chisel hammer (Les)	excavator with 36-in. bucket (Les)	cold planer teeth; all out crater; new teeth, new blade; 12 breaks

Table A2. HMA test matrix with details.

Crater No.	Test Date	HMA Thickness (in.)	Crater Dia (in.)	Saw Cutting	Breaking	Removing	Notes
A	29-Jun	5	n/a	SW45 wheel saw (Jay)	279C CTL with moil hammer (Jay)	416D backhoe with bucket (Les)	cold planer teeth (previously used for 6 sides); saw set at 10 in.
B	29-Jun	5	n/a	SW45 wheel saw (Jay)	416D backhoe moil with hammer (Les)	416D backhoe with bucket (Les)	cold planer teeth (previously used for 6 sides); saw set at 10 in.; no spotter needed for cleaning debris
C	29-Jun	5	n/a	SW45 wheel saw (Jay)	416D backhoe moil with hammer (Les)	416D backhoe with bucket (Les)	cold planer teeth (previously used for 6 sides); saw set at 10 in.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The US Army Engineer Research and Development Center was tasked by the US Air Force Civil Engineer Center to improve the saw cutting and excavation production rates of crater repairs in thick portland cement concrete (PCC) pavements for airfield damage repair (ADR) scenarios. The concrete cutting and excavation rates, along with the required manpower, using Caterpillar SW45 and Sw60 wheel saws and Caterpillar and Volvo excavators, respectively, in 18-in.-thick PCC pavement did not meet the required production rates during the 2009 Operational Utility Assessment (OUA) in Avon Park, FL. The current ADR techniques, tactics, and procedures (TTPs) indicate cutting of pavement around a crater should be completed in 22 min or less, and excavation (breaking and removal) of the repair area should be completed in 23 min or less for an 8.5- by 8.5-ft crater. Various equipment (e.g., wheel saws, excavators, rock splitter, anchors, etc.) and methods were evaluated for sawing and removing concrete and base course material in 18- and 24-in.-thick PCC and 5-in.-thick hot-mix asphalt. This report presents the technical evaluation of various sawing and excavation equipment and methods for improving the efficiency of removing damaged pavement associated with crater repair.

15. SUBJECT TERMS

Crater
Concrete
Saw cutting
Excavation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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